SciDAC advances in beam dynamics simulation: from light sources to colliders

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Abstract. In this paper, we report on progress that has been made in beam dynamics simulation, from light sources to colliders, during the first year of the SciDAC-II accelerator project, "Community Petascale Project for Accelerator Science and Simulation (ComPASS)". Several parallel computational tools for beam dynamics simulation will be described. A number of applications in current and future accelerator facilities, e.g. LCLS, RHIC, Tevatron, LHC, and ELIC, are presented.

1. Introduction

Particle accelerators are some of most important tools of scientific discovery. They are widely used in high-energy physics, nuclear physics, and other basic and applied sciences to study the interaction of elementary particles, to probe the internal structure of matter, and to generate high brightness radiation for research in materials science, chemistry, biology, and other fields. Modern accelerators are complex and expensive devices that may be several kilometers long and consist of thousands of beamline elements. Large-scale beam dynamics simulations on massively parallel computers can help provide understanding of these complex physical phenomena, help minimize design cost, and help optimize machine operation. In this paper, we report on beam dynamics simulations in a variety of accelerators ranging from next generation light sources to high-energy ring colliders that have been studied during the first year of the SciDAC-II accelerator project.

2. Beam dynamics simulations in light sources

This work used computing resources at National Energy Research Scientific Computing Center (NERSC) supported by the U. S. Department of Energy under Contract no. DE-AC02-05CH11231.

The next generation of accelerator-based light sources will produce unprecedented photon flux, brightness, and temporal resolution. To achieve their full potential requires overcoming significant technological challenges such as producing and transporting high brightness, low emittance electron beams through the accelerator while maintaining beam quality in the presence of collective effects such as space charge, wakefields, and coherent synchrotron radiation. At LBNL, two parallel particle tracking codes, IMPACT-Z [1] and IMPACT-T [2], have been developed and used to study the electron beam generation from photoinjectors and to simulate beam transport through RF linacs. Both codes assume a quasi-static model of the beam and calculate space-charge effects self-consistently at each time step together with the external acceleration and focusing fields. There are six Poisson solvers in the IMPACT code suite corresponding to different boundary conditions. These solvers use either a spectral method for closed transverse boundary conditions, or an FFT-based Green function convolution method for open transverse boundary conditions. The parallel implementation uses a two-dimensional domain decomposition approach for the three-dimensional computational domain. New features such as a short-range and CSR wakefield, integrated Green function solver, and particle-field decomposition were added to the code. Figure 1 shows the variation in efficiency of the IMPACT-T and the IMPACT-Z codes executing on increasing numbers of cores of the Cray-XT 4 computer at NERSC. It is seen that both codes still show more than 50% parallel efficiency on one thousand processors.

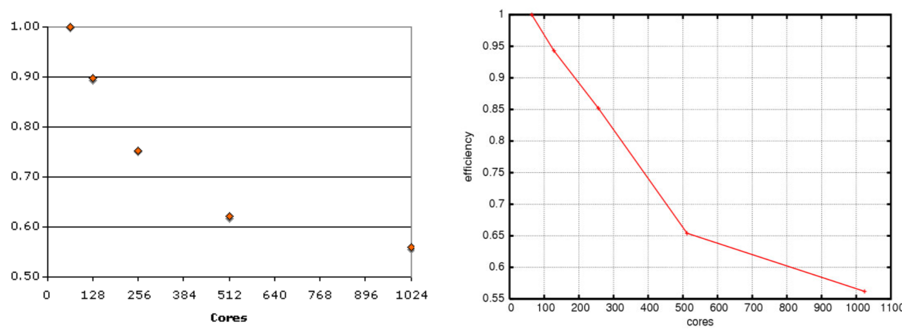

Figure 1. Parallel efficiency of IMPACT-T (left) and IMPACT-Z (right) on Cray-XT 4.

The IMPACT-T code has been used to help commission the electron generation and transport in the LCLS photoinjector. Figure 2 shows a simulation of the evolution of rms emittance of the beam with an initial 0.5 mm horizontal and vertical offset through the LCLS photoinjector. The large offset produces a difference between the horizontal and vertical emittance and significantly larger final emittance compared with the nominal design value of 1.2 mm-mrad. The IMPACT-Z code has been used to simulate the beam transport through an RF linac for a next generation FEL light source at LBNL. A large number of macropartices is needed in order to accurately predict the final uncorrelated energy spread of the electron beam due to the presence of the microbunching instability. Figure 3 shows the final energy spread after transport through the FEL linac as a function of the number of macroparticles. It is seen that final energy spread approaches a constant value as the initial number of macroparticles becomes larger than one billion.

At ANL, the ELEGANT code has been used for design, simulation, and optimization of FEL driver linacs, energy recovery linacs, and storage rings. It has been used to support for LCLS design and commissioning [3]. The ELEGANT code has recently been completely parallelized. The new version has demonstrated the ability to utilize 400 million macroparticles on 100 nodes after implementation of parallelized SDDS I/O and elimination of the master node bottleneck in particle management. Figure 4 shows growth of the microbunching instability through a number of dipoles in the Fermi/Elettra FEL linac design.

3. Beam dynamics simulations in colliders

The beam-beam interaction limits the luminosity that can be achieved in high-energy colliders. We have developed a parallel three-dimensional particle-in-cell code, BeamBeam3D, to model beam-

beam effect in high-energy ring colliders [4]. This code includes a self-consistent calculation of the electromagnetic forces (beam-beam forces) from two colliding beams (i.e. strong-strong modeling), a linear transfer map model for beam transport between collision points, a stochastic map to treat radiation damping, quantum excitation, an arbitrary orbit separation model, and a single map to account for chromaticity effects. The beam-beam forces are calculated with a parallel implementation of an FFT-based solution to the Poisson equation with a particle-field decomposition to achieve good load balance. It can handle multiple bunches interacting at multiple interaction points (IPs) in arbitrary sequences. The code was extended to include wakefield effects, and wire and crab cavity compensation components. Parallel performance of the code was measured on a variety of high performance computers and showed reasonable scalability up to thousand processors [5].

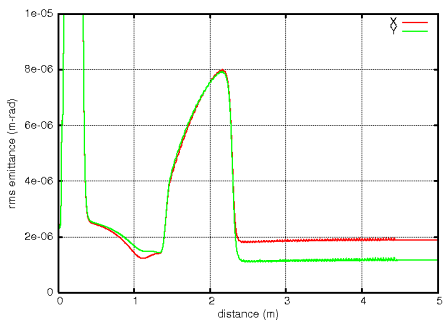

Figure 2. Transverse emittance evolution at LCLS photoinjector with initial 0.5 mm offset from IMPACT-T simulation.

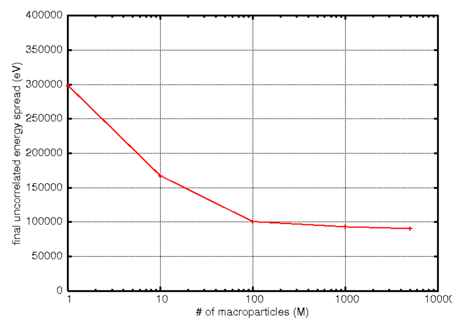

Figure 3. Final energy spread as a function of number of macroparticles from IMPACT-Z simulation.

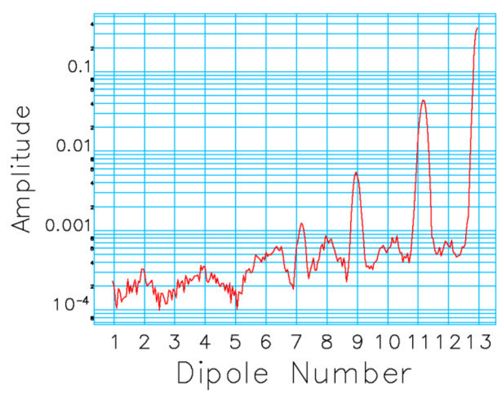

Figure 4. ELEGANT simulation of the growth of microbunching instability in the designed Fermi/Elettra FEL linac.

The BeamBeam3D code has been applied to the study of multi-bunch coherent beam-beam effects at RHIC. Each beam in the simulation has three bunches coupled via the beam-beam interaction to three bunches of the opposite beam at four interaction points. Figure 5 shows the BeamBeam3D simulation of emittance growth in tune space for the nominal working point near a half integer and for a new working point near an integer. The new working point appears to have a better performance than the nominal one.

BeamBeam3D has been extended and been used to study coherent beam-beam effects at the Tevatron. With the commissioning of electron cooling in the Recycler, the head-on beam-beam tune shifts of the two beams become essentially equal. Under these circumstances the coherent beam-beam effects may become an issue. Figure 6 shows the emittance variation among 36 proton bunches interacting with 36 antiproton bunches at both head-on and long-range IPs from a 50000 turn strong-strong Tevatron simulation The pattern of varying emittance growth that develops is characteristic of collective effects produced by the collision.

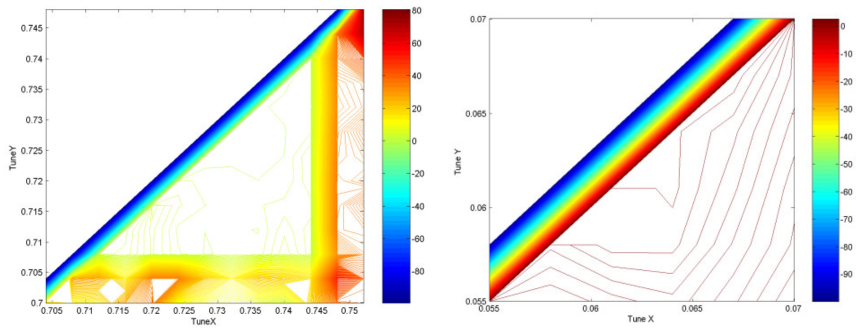

Figure 5. Emittance growth scan in tune space for a nominal working point (left) and for a new working point (right) at RHIC from BeamBeam3D simulation.

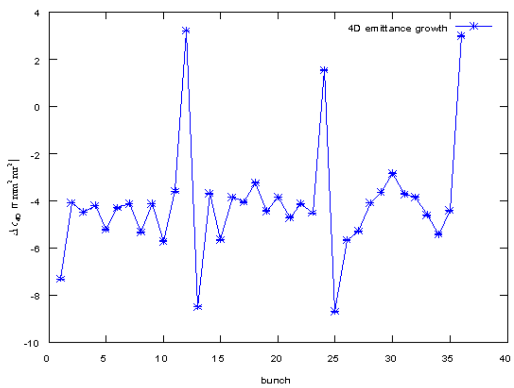

Figure 6. Emittance versus bunch number at the Tevatron from BeamBeam3D simulation.

BeamBeam3D has also been used to study long-range beam-beam effects at the LHC and to study crab cavity compensation of crossing angle collisions at the LHC upgrade. Figure 7 shows the 99.9% emittance growth with and without long-range beam-beam interactions. The simulation includes two head-on collision points (IP 1 and IP5) with 0.3 mrad crossing angle and 64 distributed long-range beam-beam interactions on both sides of the interaction region. The long-range beam-beam interaction has significantly increased the 99.9% emittance growth of the beam which characterizes the tail of the beam. Figure 8 shows the luminosity evolution with and without crab cavities for two beams colliding with 0.3 mrad crossing angle. It is seen that using a crab cavity significantly improves the luminosity at the LHC.

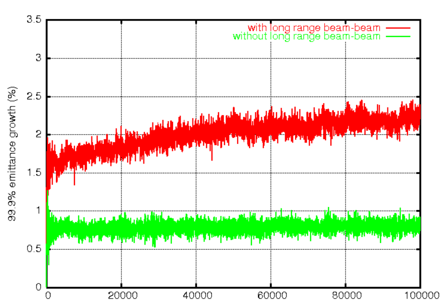

Figure 7. Emittance growth at LHC with /without long-range beam-beam interactions

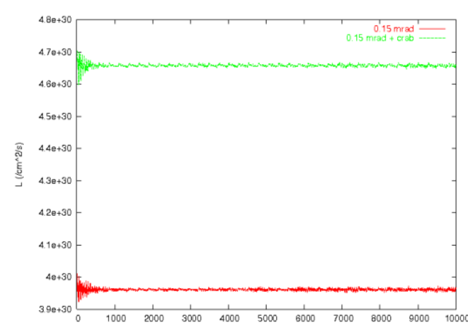

Figure 8. Luminosity evolution at LHC with /without crab cavity compensation

from BeamBeam3D simulation. from BeamBeam3D simulation.

The BeamBeam3D code has also been used to study the Electron Light Ion Collider (ELIC) proposed at Jefferson Lab. Understanding beam-beam effects at ELIC is crucial for achieving high luminosity. Figure 9 shows the luminosity as a function of electron and proton current using an old working point near the integer and a new working point towards the half integer. The new working point has significantly improved luminosity for all currents.

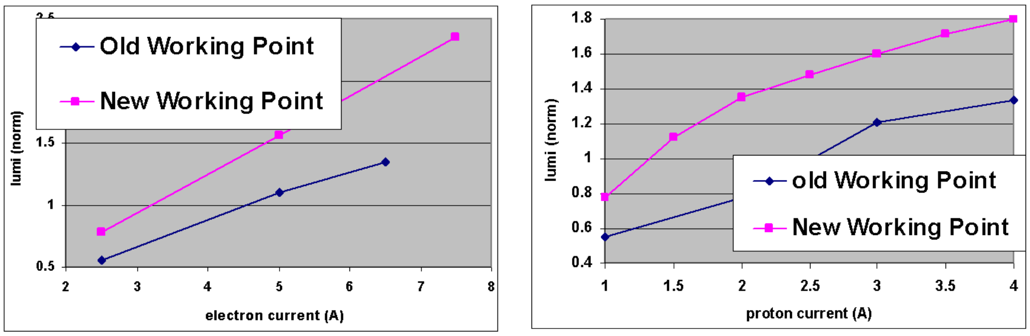

Figure 9. Luminosity as a function of electron (left) and proton (right) current at the JLab proposed ELIC collider from BeamBeam3D simulation.

At SLAC, a particle-tracking framework, PLIBB, has been developed and used to study beam-beam effects at the Tevatron, RHIC and LHC with emphasis in beam lifetime calculation using a weak-strong model [6]. The physics of the code includes intrabeam scattering, noise sources, common magnetic elements, weak-strong and strong-strong beam-beam interactions, as well as wire and electron lens compensators. Figure 10 shows the tune space footprint with/without electron lens compensation at LHC. Using an electron lens significantly reduces the size of the tune spread.

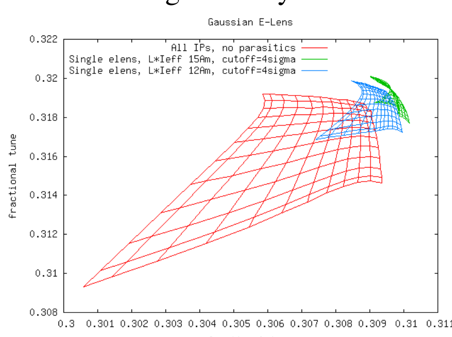

Figure 10. Tune footprint at LHC with/without electron lens from PLIBB simulation.

References

[1] J. Qiang, R.D. Ryne, S. Habib, and V. Decyk, "An Object-Oriented Parallel PIC Code for Beam Dynamics Simulation in Linear Accelerators," *J. Comp. Phys.* 163, 434-451 (2000).

[2] J. Qiang, S. Lidia, R. D. Ryne, and C. Limborg-Deprey, "A 3D Quasi-Static Model for High Brightnees Beam Dynamics simulation," *Phys. Rev. ST Accel. Beams, vol 9, 044204 (2006).*

[3] M. Borland, APS LS-287, ANL (2000).

[4] J. Qiang, M.A. Furman, and R.D. Ryne, "A Parallel Particle-In-Cell Model for Beam-Beam Interactions in High Energy Ring Colliders," *J.Comp.Phys.*198:278-294 (2004).

[5] H. Shan, E. Strohmaier, and J. Qiang, "Performance analysis of leading HPC architectures with BeamBeam3D," *Int. J. High Performance Computing Applications, 22, 21 (2008).*

[6] A. Kabel, et al., "A Parallel Code for Lifetime Simulations in hadron Storage Rings in the Presence of Parastic Weak-Strong Beam-Beam interactions," in Proc. PAC 2003, p. 3542.